

Database Management Systems

Lecture 7
Evaluating Relational Operators
Query Optimization

- queries
 - relational operators - building blocks
 - selection (σ)
 - selects a subset of records from a relation
 - projection (π)
 - eliminates certain columns from a relation
 - join (\otimes)
 - combines two relations
 - cross-product (\times)
 - returns every record in R1 concatenated with every record in R2
 - set-difference (-)
 - returns records that belong to R1 and don't belong to R2
 - union (U)
 - returns all records in relations R1 and R2

- queries
 - relational operators - building blocks
 - intersection (\cap)
 - returns records that belong to both R1 and R2
 - grouping and aggregate operators
 - every operation returns a relation
- => operations can be composed

- optimizer
 - presented with a query written in SQL
 - takes into account the manner in which data is stored
 - information available in the system catalog
 - produces an efficient execution plan for evaluating the query
 - algorithm selection for each operator
 - factors:
 - sizes of:
 - relations
 - available buffer pool
 - the existence of:
 - indexes
 - sort orders
 - buffer replacement policy
 - application order for operators

- techniques to develop algorithms for operators
 - iteration
 - examine iteratively:
 - all tuples in input relations
 - data entries in an index (provided they contain all the necessary fields)
 - smaller than data records
 - indexing
 - selection condition, join condition
 - use an index to examine only the tuples that satisfy the condition
 - partitioning
 - partition the tuples
 - decompose operation into collection of less expensive operations on partitions

- techniques to develop algorithms for operators
 - partitioning
 - partitioning techniques
 - sorting
 - hashing

- access path
 - way of retrieving tuples from a relation
 - file scan
 - index I + matching selection condition C
 - C matches I if I can be used to retrieve just the tuples satisfying C
 - example:
 - condition C : $attr \ op \ value$, $op \in \{<, \leq, =, \geq, >\}$
 - C matches I if:
 - the search key of I is $attr$ and:
 - I is a tree index or
 - I is a hash index and op is $=$
 - relation R has an index I that matches selection C
- => at least 2 access paths

- access path
 - selectivity of an access path
 - number of retrieved pages when using the access path to obtain desired tuples
 - both data and index pages are counted
 - most selective access path
 - retrieves the fewest pages
 - minimizes data retrieval costs

- general selection conditions
 - boolean combination (i.e., expression using \wedge , \vee) of terms of the form:
 - $attr \ op \ constant$
 - $attr1 \ op \ attr2$

```
SELECT *
FROM Exams
WHERE SID = 7 AND EDate = '04-01-2019'
```

$$\sigma_{SID=7 \wedge EDate='04-01-2019'}(Exams)$$

- general selection conditions
 - CNF – conjunctive normal form
 - standard form for general selection conditions
 - condition in CNF:
 - collection of conjuncts connected with the \wedge operator
 - a *conjunct* has one or more terms connected with the \vee operator
 - *term*:
 - *attr op constant*
 - *attr1 op attr2*
 - example:

$(EDate < '4-1-2019' \wedge Grade = 10) \vee CID = 5 \vee SID = 3$

rewritten as

$(EDate < '4-1-2019' \vee CID = 5 \vee SID = 3) \wedge (Grade = 10 \vee CID = 5 \vee SID = 3)$

- general selection conditions matching an index
 - index I with search key $\langle a, b, c \rangle$
 - examples

Condition	B+ tree index	Hash index
$a = 10 \text{ AND } b = 5 \text{ AND } c = 2$	Yes	Yes
$a = 10 \text{ AND } b = 5$	Yes	No
$b = 5$	No	No
$b = 5 \text{ AND } c = 2$	No	No
$d = 2$	No	No
$a = 20 \text{ AND } b = 10 \text{ AND } c = 5 \text{ AND } d > 11$	Yes (partly)	Yes (partly)

- general selection conditions matching an index
 - index I1 with search key $\langle a, b \rangle$
 - B+ tree index I2 with search key $\langle c \rangle$

Condition	Indexes
$c < 100 \text{ AND } a = 3 \text{ AND } b = 5$	<ul style="list-style-type: none"> - use I1 or I2 to retrieve tuples - check terms in the selection condition that do not match the index for each retrieved tuple

- general selection conditions matching an index
 - index I , general selection condition C (CNF)
 - I
 - hash index
 - C
 - $\wedge_{i=1}^n T_i$
 - term T_i : $attr = value$
 - I matches C if C contains exactly one term for each attribute in the search key of I

- general selection conditions matching an index
 - index I , general selection condition C (CNF)
 - I
 - tree index
 - C
 - $\bigwedge_{i=1}^n T_i$
 - term T_i : $attr \ op \ value$
 - I matches C if C contains exactly one term for each attribute in a prefix of the search key of I
 - examples of prefixes for search key $\langle a, b, c \rangle$: $\langle a \rangle, \langle a, b \rangle$

- running example - schema
 - Students (SID: integer, SName: string, Age: integer)
 - Courses (CID: integer, CName: string, Description: string)
 - Exams (SID: integer, CID: integer, EDate: date, Grade: integer, FacultyMember: string)
- Students
 - every record has 50 bytes
 - there are 80 records / page
 - 500 pages
- Courses
 - every record has 50 bytes
 - there are 80 records / page
 - 100 pages

- running example - schema
 - Students (SID: integer, SName: string, Age: integer)
 - Courses (CID: integer, CName: string, Description: string)
 - Exams (SID: integer, CID: integer, EDate: date, Grade: integer, FacultyMember: string)
- Exams
 - every record has 40 bytes
 - there are 100 records / page
 - 1000 pages

- joins

```
SELECT *
FROM Exams E, Students S
WHERE E.SID = S.SID
```

- algebra: $E \otimes S$
 - to be carefully optimized
 - size of $E \times S$ is large, so computing $E \times S$ followed by selection is inefficient
- E
 - M pages
 - p_E records / page
- S
 - N pages
 - p_S records / page
- evaluation: number of I/O operations

- joins – implementation techniques
 - iteration
 - Simple/Page-Oriented Nested Loops Join
 - Block Nested Loops Join
 - indexing
 - Index Nested Loops Join
 - partitioning
 - Sort-Merge Join
 - Hash Join
- equality join, one join column
 - join condition: $E_i = S_j$

Simple Nested Loops Join

```
foreach tuple e ∈ E do
    foreach tuple s ∈ S do
        if ei == sj then add <e, s> to the result
```

- for each record in the outer relation E, scan the entire inner relation S
- cost
 - $M + p_E * M * N = 1000 + 100 * 1000 * 500 \text{ I/Os} = 1000 + (5 * 10^7) \text{ I/Os}$

$$\begin{array}{ll} * E - M \text{ pages, } p_E \text{ records / page} * & * 1000 \text{ pages} * * 100 \text{ records / page} * \\ * S - N \text{ pages, } p_S \text{ records / page} * & * 500 \text{ pages} * * 80 \text{ records / page} * \end{array}$$

Page-Oriented Nested Loops Join

```
foreach page pe ∈ E do
    foreach page ps ∈ S do
        if  $e_i == s_j$  then add  $\langle e, s \rangle$  to the result
```

- for each page in E read each page in S
- pairs of records $\langle e, s \rangle$ that meet the join condition are added to the result (where record e is on page pe , and record s – on page ps)
- refinement of Simple Nested Loops Join

Page-Oriented Nested Loops Join

```
foreach page pe ∈ E do
    foreach page ps ∈ S do
        if  $e_i == s_j$  then add  $\langle e, s \rangle$  to the result
```

- cost
 - $M + M * N = 1000 + 1000 * 500 \text{ I/Os} = 501.000 \text{ I/Os}$
 - significantly lower than the cost of Simple Nested Loops Join
 - improvement - factor of p_E
 - choose smaller table (S) as outer table
 $\Rightarrow \text{cost} = 500 + 500 * 1000 \text{ I/Os} = 500.500 \text{ I/Os}$

* $E - M$ pages, p_E records / page * * 1000 pages * * 100 records / page *

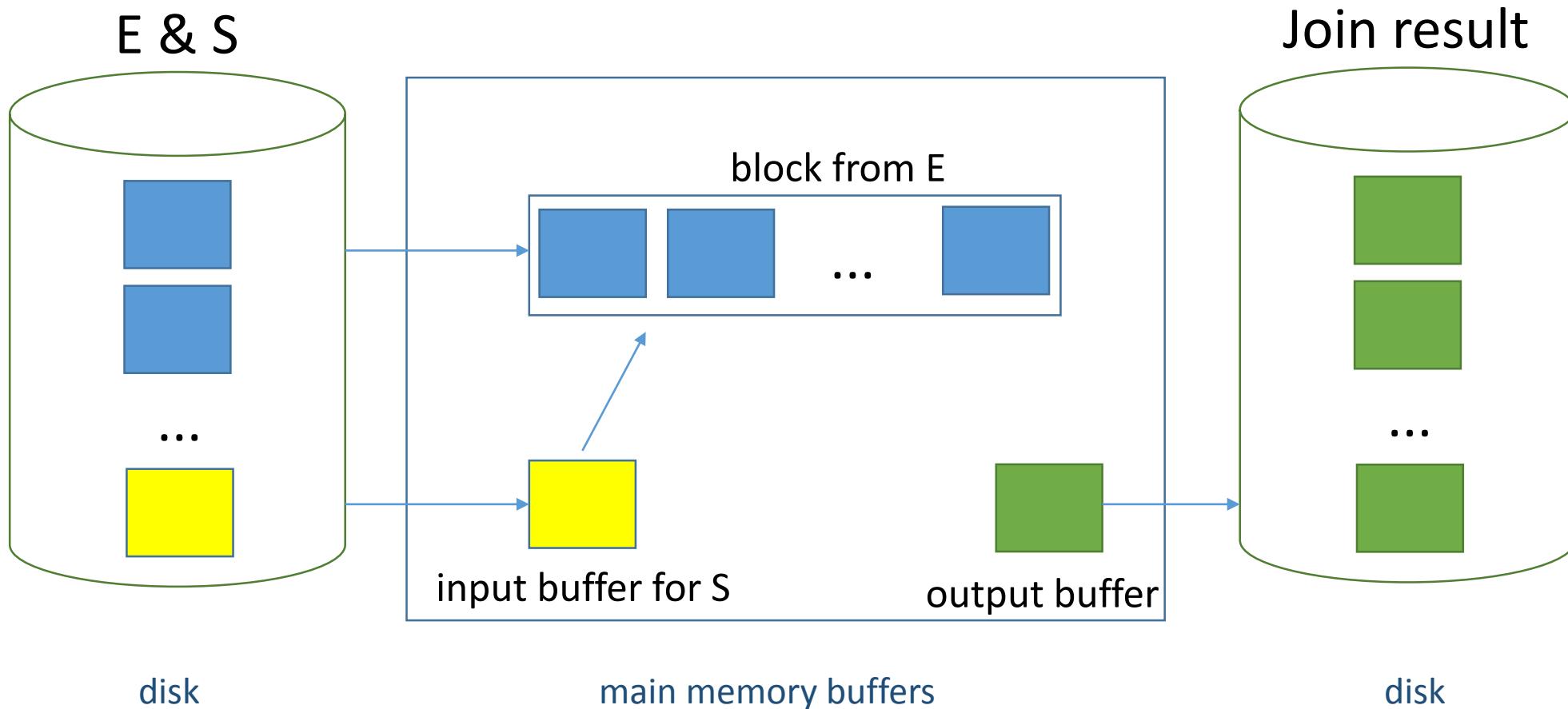
* $S - N$ pages, p_S records / page * * 500 pages * * 80 records / page *

Block Nested Loops Join

- Simple Nested Loops Join - buffer pages are not used effectively
- improvement
 - store smaller relation R1 in memory
 - keep at least 2 extra buffer pages B1 and B2
 - use B1 to read larger relation R2
 - use B2 as output buffer
 - for each tuple in R2, search R1 for matching tuples
- => optimal cost: num. pages in R1 + num. pages in R2
- refinement
 - build in-memory hash table for the smaller relation
 - I/O cost unchanged, but CPU cost is usually much lower

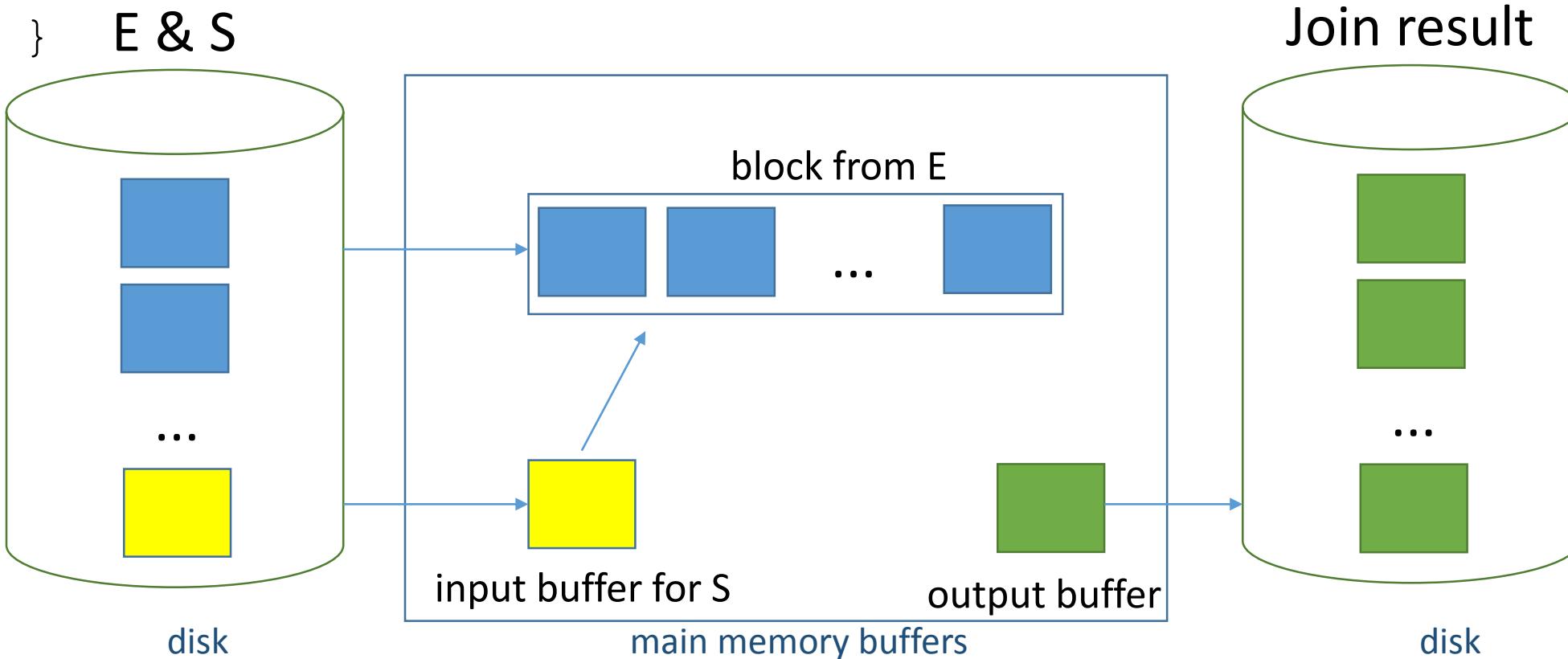
Block Nested Loops Join

- use one buffer page to scan inner table S
- use one page for the result
- use all remaining pages to read a *block* from outer table E



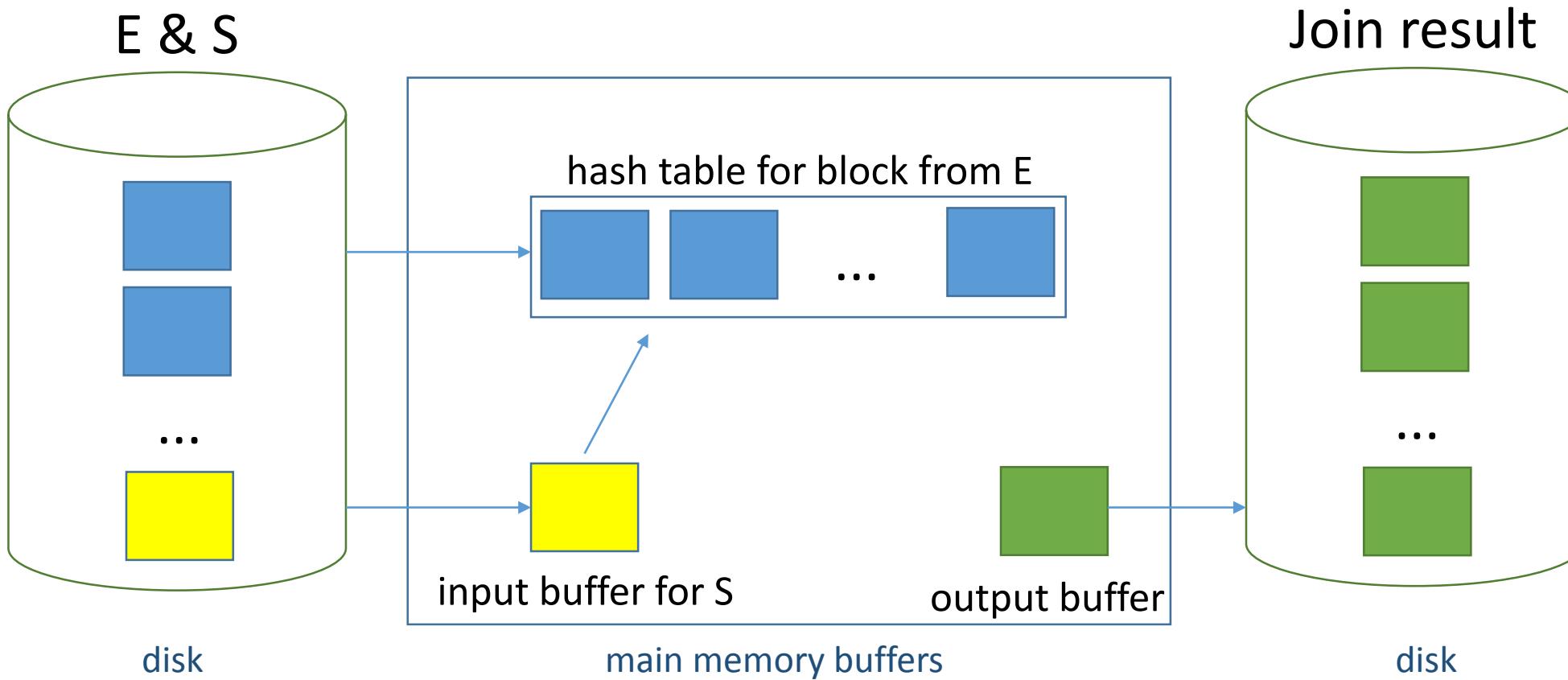
Block Nested Loops Join

```
foreach block be ∈ E do
    foreach page ps ∈ S do
    {
        for all pairs of tuples <e, s> that meet the join
        condition, where e ∈ be and s ∈ ps,
        add <e, s> to the result
```



Block Nested Loops Join

- refinement to efficiently find matching tuples
 - main-memory hash table for the block of E
 - trade-off: reduce size of E block



Block Nested Loops Join

- cost
 - scan of outer table + # outer blocks * scan of inner table
 - # outer blocks = $\left\lceil \frac{\text{number of pages in outer table}}{\text{size of block}} \right\rceil$
 - outer table: Exams (E), block of 100 pages
 - scan cost for E: 1000 I/Os
 - number of blocks: $\left\lceil \frac{1000}{100} \right\rceil = 10$
 - foreach block in E, scan Students (S): $10 * 500$ I/Os
- => total cost = $1000 + 10 * 500 = \mathbf{6000 \text{ I/Os}}$

* E - M pages, p_E records / page *

* 1000 pages * * 100 records / page *

* S - N pages, p_S records / page *

* 500 pages * * 80 records / page *

Block Nested Loops Join

- cost
 - scan of outer table + # outer blocks * scan of inner table
 - # outer blocks = $\left\lceil \frac{\text{number of pages in outer table}}{\text{size of block}} \right\rceil$
 - outer table: Exams (E)
 - buffer has 90 pages available for E, i.e., block of 90 pages
- => number of blocks: $\left\lceil \frac{1000}{90} \right\rceil = 12$
- => S is scanned 12 times
- scan cost for E: 1000 I/Os
 - foreach block in E, scan Students (S): $12 * 500$ I/Os
- => total cost = $1000 + 12 * 500 = \mathbf{7000 \text{ I/Os}}$

* E - M pages, p_E records / page *

* S - N pages, p_S records / page *

* 1000 pages * * 100 records / page *

* 500 pages * * 80 records / page *

Block Nested Loops Join

- cost
 - scan of outer table + # outer blocks * scan of inner table
 - # outer blocks = $\left\lceil \frac{\text{number of pages in outer table}}{\text{size of block}} \right\rceil$
 - outer table: Students (S), block of 100 pages
 - scan cost for S: 500 I/Os
 - number of blocks: $\left\lceil \frac{500}{100} \right\rceil = 5$
 - for each block in S, scan E: $5 * 1000 \text{ I/Os}$
- => total cost = $500 + 5 * 1000 = \mathbf{5050 \text{ I/Os}}$

$$\begin{array}{ll} * E - M \text{ pages, } p_E \text{ records / page} * & * 1000 \text{ pages} * * 100 \text{ records / page} * \\ * S - N \text{ pages, } p_S \text{ records / page} * & * 500 \text{ pages} * * 80 \text{ records / page} * \end{array}$$

Index Nested Loops Join

```
foreach tuple e in E do
    foreach tuple s in S where ei == sj
        add <e, s> to the result
```

- if there is an index on the join column of S, S can be considered as inner table and the index can be used
- cost
 - $M + (M * p_E) * \text{cost of finding corresponding records in } S)$

* E - M pages, p_E records / page *

* S - N pages, p_S records / page *

* 1000 pages * * 100 records / page *

* 500 pages * * 80 records / page *

Index Nested Loops Join

- for a record e in E :
 - cost of examining the index on S :
 - approx. 1.2 for a hash index (typical cost for hash indexes)
 - 2-4 for a B+-tree index
 - cost of reading corresponding records in S :
 - clustered index
 - plus one I/O for each outer tuple in E (typically)
 - nonclustered index
 - up to one I/O for each corresponding record in S
(worst case – n matching records in S located on n different pages!)

Index Nested Loops Join

- hash index on SID in Students
- scan Exams
 - 1000 I/Os, 100*1000 records
- for each record in Exams
 - (on average) 1.2 I/Os to obtain the page in the index and
 - 1 I/O to retrieve the page in Students that contains the matching tuple (exactly one!)

=> cost to retrieve matching Students tuples: $1000 * 100 * (1.2 + 1) = 220.000$

- total cost: $1000 + 220.000 = 221.000$ I/Os

* E - M pages, p_E records / page *

* 1000 pages * * 100 records / page *

* S - N pages, p_S records / page *

* 500 pages * * 80 records / page *

Index Nested Loops Join

- hash index on SID in Exams
- scan Students - 500 I/Os, 80*500 records
- for each record in Students
 - (on average) 1.2 I/Os to obtain the index page + the cost of reading the matching records in Exams
 - assume exams are uniformly distributed => 2.5 exams for each student ($100.000 / 40.000$)
 - the cost of retrieving the corresponding records:
 - clustered index: 1 I/O
 - unclustered index: 2.5 I/Os

=> total cost: $500 + 80*500*(1.2 + 1) = 500 + 88.000 = 88.500$ I/Os or

total cost: $500 + 80*500*(1.2 + 2.5) = 500 + 148.000 = 148.500$ I/Os

* E - M pages, p_E records / page * * 1000 pages * * 100 records / page *

* S - N pages, p_S records / page * * 500 pages * * 80 records / page *

References

- [Ra00] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems (2nd Edition), McGraw-Hill, 2000
- [Da03] DATE, C.J., An Introduction to Database Systems (8th Edition), Addison-Wesley, 2003
- [Ga08] GARCIA-MOLINA, H., ULLMAN, J., WIDOM, J., Database Systems: The Complete Book, Prentice Hall Press, 2008
- [Ra07] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems, McGraw-Hill, 2007,
<http://pages.cs.wisc.edu/~dbbook/openAccess/thirdEdition/slides/slides3ed.html>
- [Si10] SILBERSCHATZ, A., KORTH, H., SUDARSHAN, S., Database System Concepts, McGraw-Hill, 2010, <http://codex.cs.yale.edu/avi/db-book/>
- [Ul11] ULLMAN, J., WIDOM, J., A First Course in Database Systems,
<http://infolab.stanford.edu/~ullman/fcdb.html>